TECHNICAL NOTES

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No. 377

AN INTEGRATING MANOMETER FOR USE IN WIND TUNNEL PRESSURE DISTRIBUTION MEASUREMENTS

By Richard W. Noyes
Langley Memorial Aeronautical Laboratory

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Summary

A multiple manometer designed to integrate automatically the normal force over an airfoil section is described and its mathematical theory explained. The development of this instrument was conducted at the Langley Memorial Aeronautical Laboratory.

Introduction

The summation of pressure measurements to obtain total loads on any object exposed to an air stream usually involves extensive calculations. For example, the customary procedure in the reduction of data on the distribution of pressure over the surface of an airfoil is, first, to integrate the pressures obtained at a series of points located along certain "sections" taken parallel to the chord and, second, to integrate these "section loads" along the span to obtain total wing loading. Thus, for every individual set of pressure measurements made, one integration has to be performed for each section along which pressures have been measured and one to combine these section loads into a total wing load.

In an extensive research when such summation is carried out with graphical integrating machines (as is usually the case) it is obvious that a very large number of man-hours is necessary to compute the required results. To eliminate the greatest possible amount of this kind of work, when the distribution of pressure over each section is not of importance, the National Advisory Committee for Aeronautics has developed and used the manometer herein described for the automatic integration of wind tunnel pressure distribution data. This instrument gives total section loads automatically, leaving only one integration to be done to determine the total wing loading. It is impossible to obtain pitching moments, but it may be seen from Reference 1 that this also could be accomplished by use of additional manometer units working on the same principle as those described.

Discussion

The mathematical basis for the design of a manometer built to indicate automatically the normal force coefficient of an airfoil of unit span is the general expression,

$$C_N' = \frac{\int_0^c f\ (x)\ d\ x}{q\ c} \tag{1}$$

where C_N' = the section normal force coefficient,

$\int_0^c f\ (x)\ d\ x$ = the summation of the forces normal to the chord,

q = the dynamic pressure,

and c = the length of the chord.

The exact solution of this equation by graphical integration of $f\ (x)\ d\ x$ would be possible if a curve representing the true pressure distribution could be plotted. Similarly, if the equation of the curve were known, exact analytical integration might be possible. In practice neither the true curve nor its equation can be obtained, but approximate graphical integration of a smooth curve drawn through a limited number of known ordinates of the true curve has proved sufficiently precise.

A study of several methods of numerical integration has shown that a certain application of Gauss' method gives results agreeing very closely with graphical integration. The fundamental equation of this method is the approximate integral,

$$\int_0^c f\ (x)\ d\ x = H_1\ y_1 + H_2\ y_2 + - - - H_n\ y_n \tag{2}$$

where $H_1 - - - H_n$ are factors depending upon the spacing of the ordinates and having the dimension of length.

$y_1 - - - y_n$ are ordinates of the true curve at certain specified abscissas.

n = the number of ordinates.

A manometer designed to perform the summation of the products indicated in this equation and thereby to give an approximate solution of equation (1) is shown schematically in Figure 1. In this figure, A = total free surface area of the manometer reservoir. Individual manometer tubes have areas,

$$a_1 = \frac{H_1}{k}$$

$$a_2 = \frac{H_2}{k}$$

$$a_n = \frac{H_n}{k}$$

where k = a constant having the dimension 1/length. The liquid heads balancing the pressures at the wing orifices are,

$y_1 - - - y_n$

and Y = the change in head in the reservoir, $L' - L$, due to the displacements in the tubes.

A small auxiliary tube not shown in the figure indicates Y which, as demonstrated below, is a measure of C_N' on the single surface, upper or lower, to which the manometer is connected.

Equation (2), written in terms of the tube areas, gives

$$\begin{aligned}\int_0^c f(x)\,d\,x &= k\,a_1\,y_1 + k\,a_2\,y_2 + - - - k\,a_n\,y_n \\ &= k(a_1\,y_1 + a_2\,y_2 + - - - a_n\,y_n) \qquad (3).\end{aligned}$$

The total volumetric displacement in the tubes relative to the original liquid level L' must equal the corresponding displacement in the reservoir $A\,Y$, giving the relation,

$$A\,Y = a_1(y_1 - Y) + a_2(y_2 - Y) + - - - a_n(y_n - Y).$$

Expanding this expression and rearranging the terms gives

$$a_1\,y_1 + a_2\,y_2 + - - - a_n\,y_n = [(a_1\,Y + a_2\,Y + - - - a_n\,Y) + A\,Y]$$

which, when substituted in equation (3), results in the following integral expressed in terms of the single variable Y:

$$\int_0^c f(x)\,d\,x = k[(a_1\,Y + a_2\,Y + - - - a_n\,Y) + A\,Y].$$

Integrating, this equation becomes,

$$f(x) = k[\Sigma(a\,Y) + A\,Y] = k(\Sigma\,a + A)\,Y$$

where $f(x)$ is the area of the section normal force diagram for one surface. Hence, from equation (1),

$$C_N' = \frac{f(x)}{q\,c} = \frac{k(\Sigma a + A)}{q\,c} Y,$$

or, placing
$$\frac{k(\Sigma a + A)}{c} = K$$

$$C_N' = \frac{K\,Y}{q} \tag{4}$$

In other words, the normal force coefficient equals the change in height of the liquid in the manometer reservoir, times a constant, divided by the dynamic pressure expressed in consistent units.

It has been pointed out that the above method of automatic integration applies only to the section pressures over one surface of the airfoil. Therefore, it is necessary to have a similar manometer to integrate the pressures over the other surface. It is apparent that the algebraic difference of the displacements, Y upper and Y lower in the two manometers, multiplied by the constant, K/q gives the total section normal force coefficient.

The manometer assembled for use in the investigation reported in Reference 2 is illustrated in Figure 2. Pressures were measured over five sections along the span of the airfoil model. The orifices on the upper surface were attached to the manometer units on the right and those on the lower surface to the units on the left. The "indicating tube" rack is seen in the center. Records of the liquid heights in those tubes were obtained as shadowgraphs on sheets of photostatic paper placed against the lower surface of the tubes.

Figure 3 shows the details of construction of two sample manometer units. Both parts of each unit were made of steel 2 inches thick. The outside diameter of the inner block and the recess in the outer block were accurately machined so that when they were assembled, as shown on the right in the figure, the annular space between them served for the reservoir of the specified area. Small plugs set into the bottom of the recess supported the inner "tube block" so that free circulation of alcohol to the individual manometer tubes was obtained. The latter, as shown on the left of the figure, were holes reamed in the tube block. Their upper ends were sealed by steel plugs carrying nipples to which rubber tubes leading to the wing model were attached. The short tube extending from the bottom of the outer block was connected by suitable glass and rubber tubing to the indicating tubes seen in Figure 2. Table I gives the constants of integration for the tube spacing indicated and the corresponding critical dimensions of the manometer.

Suggestions for Future Design

The manometer described above was designed for use with mercury for a manometer liquid. Service results showed this medium to be unsatisfactory and alcohol had to be used instead. However, with special precautions to insure absolute cleanliness of all parts of the apparatus and to prevent the formation of oxide films on the free surfaces, mercury could be used.

Some transparent material would be preferable to steel for construction of the tubes. With steel, checking of the manometer for leaks and blocking requires special apparatus, and observation of the liquid levels during a test is never possible. Slightly oversize, uniform bore glass tubing, corrected for exactly the proper internal area by means of inserted wires, would probably be satisfactory.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 17, 1931.

References

1. Munk, Max M. : The Spacing of Orifices for the Measurement of Pressure Distribution. N.A.C.A. Technical Note No. 230, 1926.

2. Knight, Montgomery and Noyes, Richard W. : Span-Load Distribution as a Factor in Stability in Roll. N.A.C.A. Technical Report No. 393, 1931.

TABLE I

Manometer Specifications

*Tube spacing in per cent of chord	*Gauss constants of integration for c = 10 in.	Manometer constant k	Manometer tube areas sq. in.	Total manom. tube area Σa sq.in.	Reservoir area A sq.in.
X_1 = 1.3047	H_1 = 0.33336	1.037	a_1 = .321	9.640	3.30
X_2 = 6.7469	H_2 = 0.74729	1.037	a_2 = .720		
X_3 = 16.030	H_3 = 1.0954	1.037	a_3 = 1.056		
X_4 = 28.330	H_4 = 1.3463	1.037	a_4 = 1.298		
X_5 = 42.556	H_5 = 1.4776	1.037	a_5 = 1.425		
X_6 = 57.444	H_6 = 1.4776	1.037	a_6 = 1.425		
X_7 = 71.670	H_7 = 1.3463	1.037	a_7 = 1.298		
X_8 = 83.971	H_8 = 1.0954	1.037	a_8 = 1.056		
X_9 = 93.253	H_9 = 0.74729	1.037	a_9 = .720		
X_{10} = 98.695	H_{10} = 0.33336	1.037	a_{10} = .321		

$$K = \frac{k(\Sigma_a + A)}{c} = \frac{1.037\ (9.640 + 3.30)}{10} = 1.342$$

*From Reference 1.

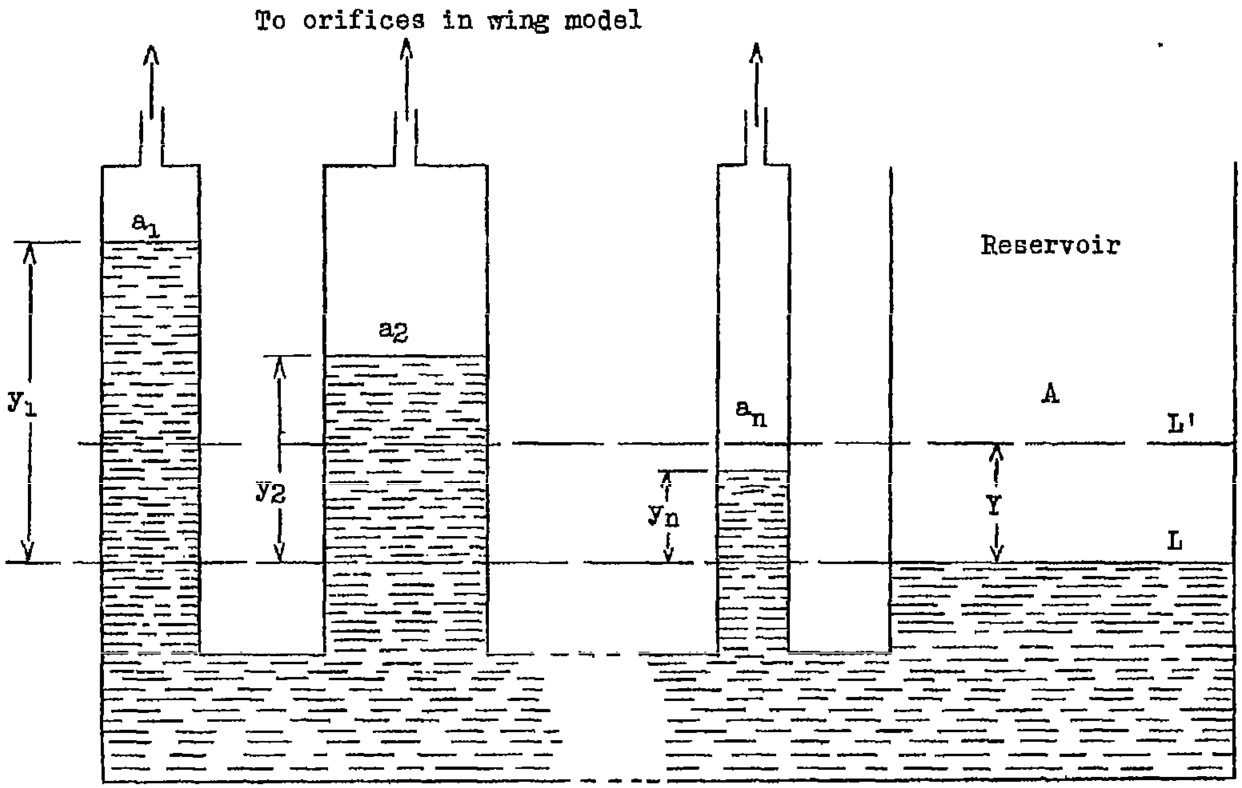

Fig.1 Schematic diagram of integrating manometer.

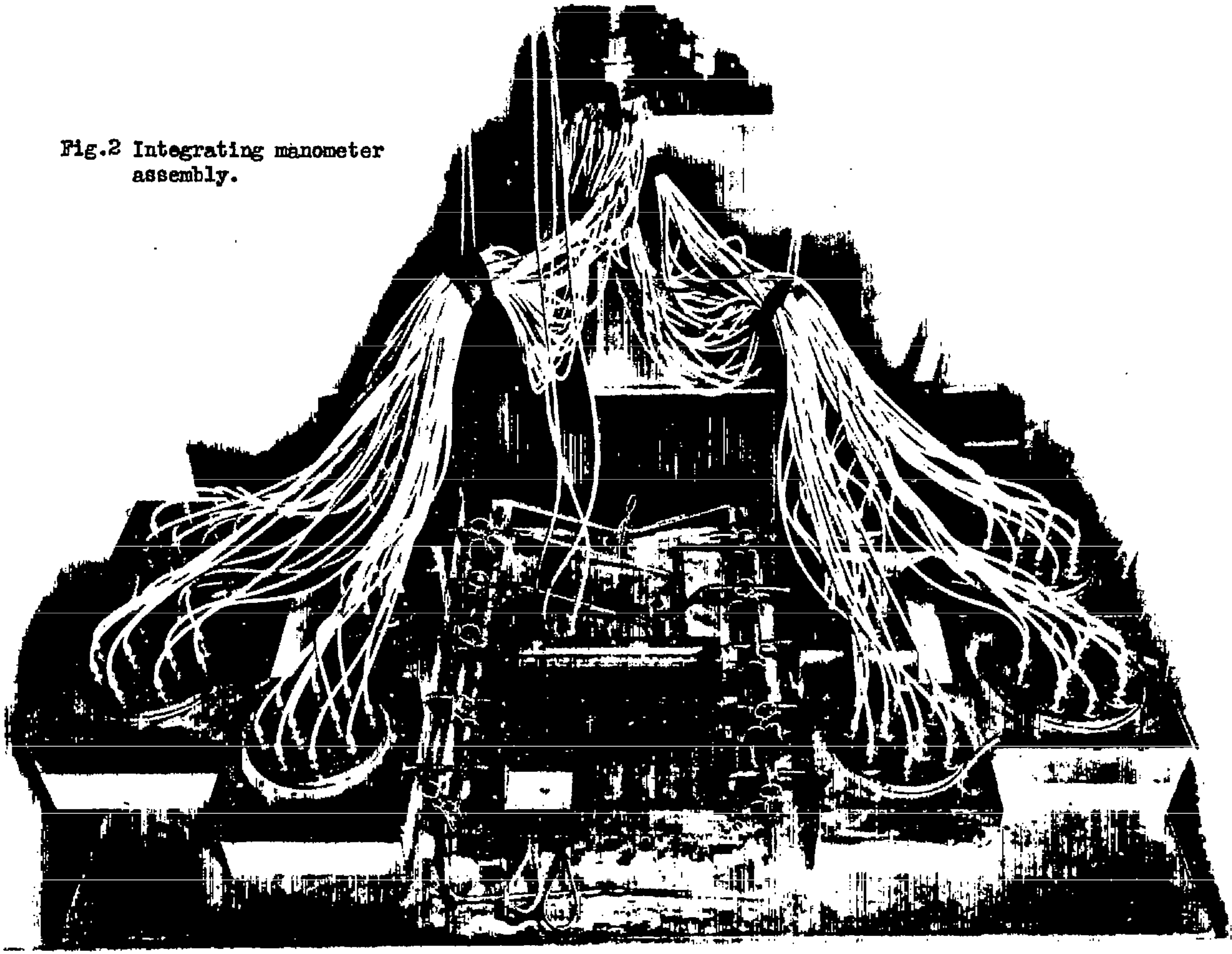

Fig.2 Integrating manometer assembly.

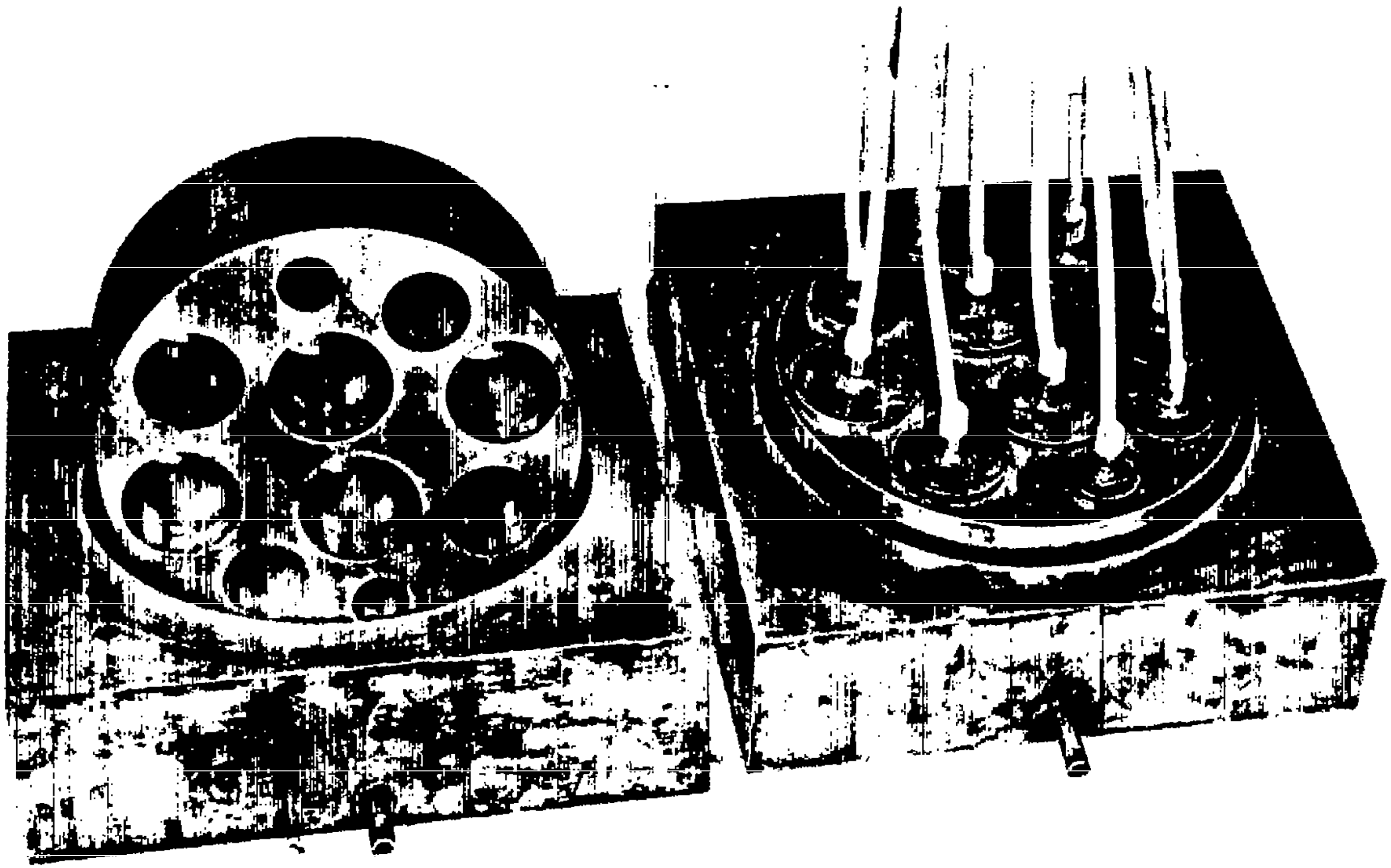

Fig.3 Integrating manometer units.